Statistical Properties of the Acoustic Field in Inhomogeneous Oceanic Environments

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LONG-TERM GOALS

- To develop an effective method of description of statistical properties of acoustical signals and calculation of false alarm rate for a given probability distribution of locations of acoustic source(s) in space.

- To quantify the degree to which uncertainty in the knowledge of cross-range variation of environmental parameters and their variation in time (or purely statistical information on the variations) degrades the ability to detect, locate, and track targets acoustically.

OBJECTIVES

1. To develop an effective numerical algorithm of calculation of second statistical moments of the acoustic signals measured by a set of receivers located on sea bottom or arbitrarily distributed in space for inhomogeneous ocean waveguide (including the case of uneven bottom) in terms of probability distributions of source location.

2. To investigate probability distributions of acoustical signals for typical environments including both deep water and littoral cases.

3. To develop an efficient formalism of transferring uncertainty in the 4-D spatial-temporal fields of environmental parameters into uncertainties of observable acoustic quantities.

4. To quantify the amount of environmental information necessary to achieve a specified accuracy of acoustic field modeling and to determine, for various nearshore hydrodynamic processes of interest, when 2-D (as opposed to 3-D and 4-D) environmental and propagation models are acceptable.

5. To develop a numerical algorithm for predicting statistical moments of acoustic signals in underwater waveguides with horizontally-inhomogeneous and time-dependent parameters.

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APPROACH

Our approach to modeling acoustic effects of cross-range environmental gradients, oceanic currents, and time-dependence of the sound speed and the problem geometry, is based on considering these effects as perturbations with respect to sound propagation in a range-dependent, motionless, stationary waveguide. The problem is solved analytically for the three leading terms of the perturbation series. Account of the second-order terms is crucial because it is these terms that are responsible for ray travel time and mode phase biases. The perturbation solution is used to determine statistical properties of various acoustic observable quantities in terms of respective statistical properties of environmental parameters. The task of relating statistical properties of the sound field to statistical properties of the environment is greatly facilitated by the fact that the perturbation theory gives variations in travel times and other acoustic quantities as integrals in the source/receiver vertical plane of certain functions of cross-range gradients and time derivatives of environmental parameters. Kernels of the integrals are determined by the acoustic field in an unperturbed, stationary, range-dependent environment and are independent of the currents, the cross-range environmental gradients and the time derivatives.

To quantify uncertainties in the acoustic field and associated probabilities of the detection and false alarm rate we use the concept of a scattering matrix (SM) for acoustic modes. SM describes the process of transformation of modes when propagating through an inhomogeneous region. SM depends on the parameters of the inhomogeneities but does not depend on coordinates of the source and receivers. Thus the functional dependencies on the environmental parameters and positions of the source and receivers are multiplicative and can be studied separately. In particular, if the SM is exactly known and position of the source is unknown, uncertainties of the detection can be expressed in terms of convolution of SM with an assumed probability distribution of the source location. On the other hand, if SM is not exactly known, additional uncertainty in source detection can be expressed in terms of statistical moments of SM itself.

The key individuals currently involved in this work are Oleg A. Godin (CIRES/Univ. of Colorado and NOAA/ETL) and Alexander G. Voronovich and Valery U. Zavorotny (NOAA/ETL). Dr. Voronovich is primarily responsible for developing and implementing the scattering matrix formalism and an improved description of nonlinear internal gravity waves. Dr. Zavorotny is involved in numerical simulations of the acoustic field and contributes his expertise on waves in random media. Dr. Godin takes the lead in the theory and modeling of the 3-D and 4-D effects in underwater sound propagation.

WORK COMPLETED

Statistical properties of travel time of sound waves reflected or refracted at a 3-D rough surface have been studied within the ray theory (Godin and Fuks, 2003; Fuks and Godin, 2003).

To account for the ocean's nonstationarity, which is represented by currents and temporal variation of the sound speed, improved techniques of sound propagation modeling within the parabolic approximation, the ray theory, and the "vertical modes – horizontal rays" approximation have been developed (Godin, 2002a-d).

An algorithm has been developed and implemented to calculate statistical moments of travel time, grazing and azimuthal angles, ray displacement, and frequency spectra of acoustic signals propagating in a waveguide with deterministic and stochastic inhomogeneities (Godin, 2003b; Godin et al., 2003).

Validity of Fermat's principle of stationary travel time and eikonal has been established for acoustic waves in temporally-varying media (Godin and Voronovich, 2003; Voronovich and Godin, 2003). This result extends known properties of rays in time-independent environments to time-dependent ones and serves as a powerful tool of analysis of acoustic fluctuations in a nonstationary ocean.

Hydrodynamic part of the work included extension of the previously developed "2.5- layer" model of strongly non-linear internal wave solitons to the case where a steady current with a constant shear is present. The layer with current should have zero Brunt-Vaisala frequency. If the second layer is also homogeneous, the expression for potential function can be written explicitly as a ratio of polynomials of the third and fifth order.

The scattering-matrix approach was applied to the case of sound propagation over uneven bottom (which was simulated by a 3-D "hill") in the shallow-water environment. The novel feature is consideration of this situation in the 3-D case with a proper account of the acoustic modes' interaction. It was assumed that the acoustic field is received by a billboard array, and the presence and position of the point source was inferred by numerical back-propagation of the received field ("time reversal"). This procedure was accomplished both in the ideal situation of a homogeneous Pekeris waveguide, and with account of the "hill" on the bottom. In both cases back-propagation was simulated as if the bottom was plane and horizontal. The quality of the source detection was investigated.

Acoustic filed scattering by a random field of internal waves has been investigated in the framework of multiple-scattering theory. Calculation of the average field has been studied. Both full-wave 3-D and 2-D cases have been considered. The purpose of this research is to investigate the importance of 3-D effects.

With funds from a grant N00014-03-IP2-0085 to support a publication in English of a Russian book on the history of Russian underwater acoustics, three review articles have been commissioned on development of the understanding of the physics of underwater sound propagation, sound scattering in the ocean, and ambient noise and underwater communication. The articles will review the few key subjects not covered appropriately in the original. The articles are been written by veteran Russian experts in the respective fields. In order to select translators for the book, a competition was organized among experienced translators based in Russia. Trial translations they submitted are currently being evaluated.

RESULTS

In a study of acoustic uncertainty associated with roughness of ocean surface and bottom, it is found that surface roughness typically decreases the mean travel time in the case of large-scale roughness where a single specularly-reflecting point moves randomly around its unperturbed position, resulting in a negative travel-time bias (towards early echoes). In the opposite limiting case of multipath propagation, where many specular points exist on a random surface, the travel-time bias is always positive. These conclusions refer to sound scattering from rough surfaces in homogeneous media. Scattering in inhomogeneous media needs to be studied separately.

A novel perturbation theory has been developed within the ray approximation to describe acoustic fluctuations in an environment where a multiple forward scattering on weak random inhomogeneities accompanies a strong, regular refraction, which is typical to oceanic waveguides. Unlike previous

perturbation approaches, the new theory can be applied to ray families having an arbitrary number of caustics and utilizes only quantities routinely calculated by existing range-dependent ray codes. The perturbation theory reduces the problem of determining statistical moments of travel time, arrival angles, and of the other parameters of ray arrivals to calculation of certain quadratures along the unperturbed ray path. For the perturbation theory to be valid, ray displacement due to environmental perturbations should be small compared to their spatial scale. In the problem of sound scattering by internal waves in the ocean, it has been found that conditions of applicability of the ray perturbation theory to sound scattering in the source-receiver vertical plane are more restrictive than for scattering out of the plane (i.e., for horizontal refraction). In deep ocean, the perturbation theory can be applied to simulate in-plane scattering at propagation ranges of a few hundred kilometers at most. Restrictions prove to be less severe for steep than for shallow eigenrays.

In investigation of 4-D acoustic effects, frequency variations have been quantified within the ray theory for sound propagating in deep water through random internal waves with the Garrett-Munk spectrum and in shallow water through a train of internal wave solitons. Temporal variation of the sound speed leads to acoustic frequency wander which cannot be distinguished at the receiver end from the Doppler shift due to a source motion. Figure 1 shows the false Doppler shift calculated for a 13.5 km track between a sound source and two receivers in a vertical line array under conditions of the 1995 SWARM experiment (Apel *et al.*, 1997). Internal tide generated at the shelf break was a major source of environmental variability at the SWARM site, with up to 10 m vertical displacements in 80 m-deep ocean. Note that the relative frequency variation of 10^{-5} approximately corresponds to a Doppler shift due to a source-receiver relative motion with the radial velocity of 1.5 cm/s. In deep water, the frequency wander due to internal waves accumulates with the propagation range and reaches values shown in Figure 1 at source-receiver separations of ~ 700 km.
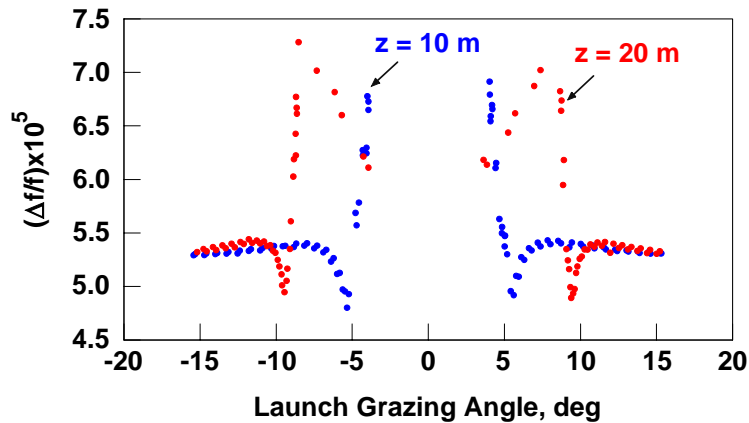

Figure 1. Frequency wander on various eigenrays for sound propagation along wave front of an internal wave soliton
[Relative perturbations in sound frequency vary from 4.7·10^{-5} to 7.4·10^{-5}]

In the investigation of dynamics of internal wave solitons, it was found that the 2.5-layer model with constant shear, which is described by five dimensionless parameters, can be applied to a variety of practical situations. It can describe both positive and negative soliton profiles. In particular, when applied to the case of COPE experiment (Stanton and Ostrovsky, 1998), the presence of a current with a moderate shear results in a significant shortening of the soliton length. In principle, the solitons of

this type could exist even in the case when stratification is unstable within the linear approximation. This situation will be investigated at the next stage of the project.

In the study of the quality of source detection by back-propagation of the acoustic field received by bill-board array it was demonstrated that, if the presence of the "hill" located between the source and the receiver is ignored, the image of the source is significantly deteriorated and splits into two blurred focuses. The brightness of the focuses is comparable to the homogeneous case. This indicates that the detection of the acoustic source can be achieved even without accounting for the bottom topography in this case, however determination of the source location is unreliable.

In the investigation of the average acoustic field, the Dyson equation in the Bourret approximation for calculation of the average Green function has been obtained in 2-D and 3-D cases. The equation determining modal structure of the average acoustic field generally includes a non-local integral term in addition to usual differential operator. When perturbation analysis is applicable, the expression for the decrement of attenuation of the average field has been obtained. Preliminary analysis shows that neglecting the 3-D effects could lead to a $O(1)$ error in determining decrement of attenuation.

IMPACT/APPLICATIONS

The most immediate impact of this work will be on the use of deterministic models of underwater sound propagation for making tactical decisions. Results of this work will quantify, in a statistical sense, reliability of predictions for various acoustic observables obtained assuming range-dependent ocean and disregarding horizontal refraction and effects due to ocean currents and time-dependence of the environmental parameters.

This work should also have an impact on design of detection algorithms. The algorithms should be made insensitive to the components of the acoustic field which are most affected by the unknown inhomogeneities of the ocean waveguide associated, e.g. with internal wave solitons or bottom profile features. Those field configurations are described by eigenvectors of scattering matrix. The results obtained will allow quantifying the effects of uncertainties in the description of oceanic environment on the probability of detection and the false alarm rate.

RELATED PROJECTS

Experimental Verification of a Horizontal-Refraction-Tomography Technique Using North Pacific Acoustic Laboratory Data (N00014-02-IP2-0035).

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